Influence of temperature and strain rate on the formability of aluminium alloys: Comparison between experimental and predictive results

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INFLUENCE OF TEMPERATURE AND STRAIN RATE ON THE FORMABILITY OF ALUMINIUM ALLOYS : COMPARISON BETWEEN EXPERIMENTAL AND PREDICTIVE RESULTS

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ABSTRACT: The use of sheet metal forming processes can be limited by the formability of materials, especially in the case of aluminium alloys. To improve the formability, warm forming processes can be considered. In this work, the effects of temperature and strain rate on the formability of a given aluminium alloy (AA5086) have been studied by means of both experimental and predictive approaches. Experimental tests have been carried out with a Marciniak stamping experimental device. Forming limit curves (FLCs) have been established on a temperature range going from ambient temperature to 200°C and on a strain rate range going from quasi-static up to $2s^{-1}$. In order to predict the experimental temperature and strain rate sensitivities, a predictive model based on the finite element simulation of the classical Marciniak and Kuczynski (M-K) geometrical model is proposed. The limit strains obtained with this model are very sensitive to the thermo-viscoplastic behaviour modeling and to the calibration of the initial geometrical imperfection controlling the onset of necking.

KEYWORDS: Forming Limit Curves (FLCs), aluminium alloys, temperature, strain rate

1 INTRODUCTION

Sheet metal forming processes are widely used in industry. Aluminium alloys represent an interesting alternative, especially in the transportation field due to their high-strength to weigh ratio and corrosion resistance. Nevertheless, aluminium alloys exhibit generally a low formability at ambient temperature in comparison with traditional mild-steels. Under warm forming conditions, the formability of aluminium alloys can be greatly improved. For these conditions, the strain rate can play a predominant role in determining the sheet metal formability. Hence, the characterisation of aluminium alloy formability at elevated temperatures and for a wide range of strain rates is essential for controlling the success of the forming process.

To assess the sheet metal formability, the Forming Limit Diagram (FLD) has been extensively adopted in experimental and numerical works. Experimentally, temperature and strain rate effects on formability have been studied by some authors, as for example: Naka et al. [1] for AA5083, Li and Gosh [2] for AA5754, AA5182 and AA6111, Mahabunphachai and Koç [3] for AA5052 and AA6061 or recently Wang et al. [4] for AA2024. For these investigations, it was shown that temperature (ranging from 150°C to 300°C) had a significant positive effect on formability whereas the increase of strain rate had generally a negative effect on formability.

The experimental characterization of formability is a very complicated and time consuming procedure. Many analytical and numerical models have been proposed to analyze the necking process and then predict the formability. The Marciniak-Kuczinsky (M-K) theory is widely used due to its simplicity. The Forming Limit Curves (FLCs) from the M-K model are generally given at ambient temperature and without strain rate consideration. Very few studies are concerned with temperature and strain rate effects. The main disadvantage of the M-K model is that the results are greatly dependent on the initial imperfection value (f_0) and on the modelling of the mechanical behaviour of metallic sheets [5]. Very little work about the M-K model was presented at high temperature, much rare for the coupling of temperature and strain rate. Khan and Baig [6] have recently determined FLCs for AA5082 under different temperatures (from ambient to 200°C) and strain rates (up to $10s^{-1}$). A nega-

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tive strain rate effect at 200°C was found but this work did not mention the initial imperfection value. The FLCs of AA5182 from 25 to 260°C were determined by Abedrabbo et al. [7], they have showed an improvement of the formability with temperature. Unfortunately, these two studies were not validated by experiments.

In this work, the experimental formability of AA5086 at different temperatures (20, 150 and 200°C) and strain rates (0.02, 0.2 and 2 s^{-1}) is firstly evaluated by means of a Marciniak test setup. Uniaxial tensile tests for the same range of temperatures and strain rates are proposed to identify three hardening laws (power, saturation and mixed) for this material. Finally, the predicted FLCs are determined from a dedicated FE M-K model for the same conditions of temperature and strain rate. The comparison between numerical and experimental results is given and the choice of initial imperfection calibration strategy and hardening law is discussed.

2 EXPERIMENTAL RESULTS

2.1 TEST SETUP

The formability tests at different temperatures and forming speeds have been carried out by means of a Marciniak test setup. More details are given in [8]. The specimen is heated by heat conduction thanks to two independent dedicated heating systems: eight heaters plugged into the up and bottom blank holders and one heater into the punch (Fig. 1).

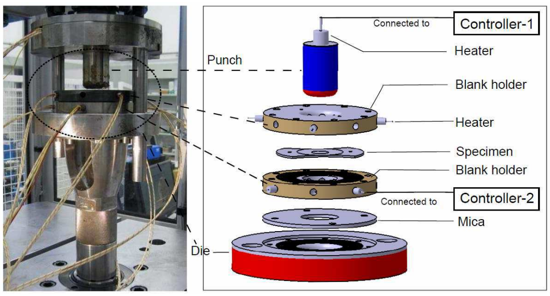

Fig. 1 Marciniak heating apparatus.

Deformations on specimen in plane strains are followed by a high speed and resolution camera and evaluated by digital image correlation (CORRELA) during the test. To ensure a strain localization in the center of specimens, a non-uniform thickness is defined for all the specimens. The initial sheet thickness is 2mm and it is reduced to 0.8mm in the central part. The change in the specimen width permits to cover the whole FLD, from uniaxial to biaxial stretching (Fig. 2).

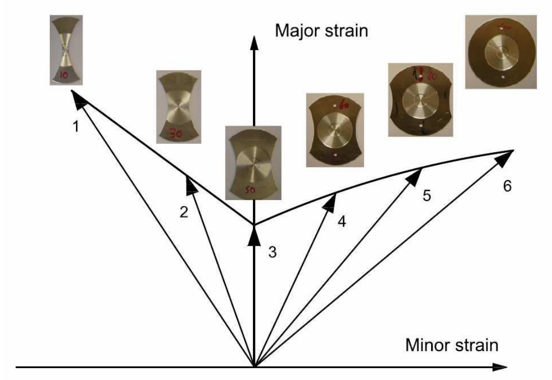

Fig. 2 Specimen widths and strain paths [8].

2.2 FORMING LIMIT CURVES

The forming limit curves are obtained by a position-dependent criterion inspired by the international standard ISO 12004-2. All the experimental FLCs for the different testing conditions are shown in Fig. 3. The forming speeds of 0.1, 1 and 10mm/s correspond respectively to strain rates of 0.02, 0.2 and 2 s^{-1}.

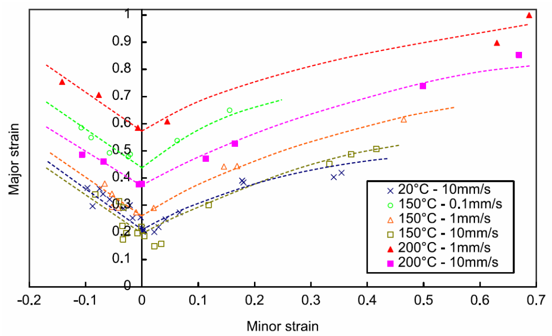

Fig. 3 Experimental FLCs for AA5086

Fig. 3 shows that temperature and strain rate affect significantly the level but not the shape of forming limit curves. FLCs at ambient temperature for different strain rates are not presented since this material is not sensitive to strain rate at this temperature. As already observed in literature for other aluminium alloys, temperature has a positive effect on formability and strain rate has a negative effect. At 150°C, when the forming speed decreases from 10mm/s to 1mm/s and 0.1mm/s, the increase of major strain value under plane strain condition (FLC_0) is about 35% and 90%, respectively. One can notice that the positive effect of temperature can be completely inhibited by the increase of forming speed. As an example, the formability at 150°C and 0.1mm/s is better than the one at 200°C and 10mm/s.

3 PREDICTIVE MODEL

The difficulty in implementing realistic hardening in analytical models based on M-K theory, especially with temperature and strain rate functions, limits its application. To overcome this difficulty, a finite element (FE) M-K model has been proposed by Zhang et al. [9] to predict FLCs (Fig. 4).

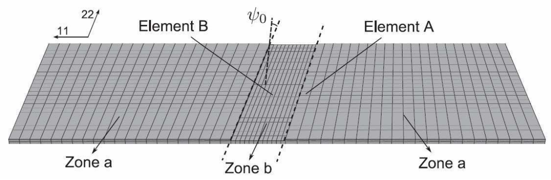

Fig. 4 *FE M-K model*

An initial imperfection value is introduced by defining two different thicknesses in zone a (t_a) and zone b (t_b). Different initial imperfection values of $f_0 = t_b/t_a$ can be obtained by changing t_b values. When the equivalent plastic strain increment ratio of element B and A exceeds 7 [9], localized necking is assumed to occur and the corresponding major and minor strain of element A are noted as one point on the FLC. Through ABAQUS user-defined subroutine UHARD, different hardening laws can be implemented into the FE M-K model to describe the material flow stress.

3.1 RHEOLOGICAL BEHAVIOUR

Results from M-K model are very sensitive to the modelling of the rheological behaviour of the material. In order to identify the hardening behaviour of the AA5086, uniaxial tests have been carried for the same range of temperatures and strain rates already measured for the previous Marciniak tests.

To describe the thermo-viscoplastic behaviour of AA5086, three different types of hardening models are selected, A power law (*Ludwick*) model, a saturation (*Voce*) model and a mixed type (*H-V*) model. The H-V model was proposed by Sung et al. [10]. The proposed hardening models are respectively shown in Eq (1) to Eq (3):

$$\bar{\sigma} = \sigma_0(T) + (K_0 - K_1 T)\bar{\varepsilon}_p^{(n_0 - n_1 T)}\dot{\bar{\varepsilon}}_p^{m_0 \exp(m_1 T)} \tag{1}$$

$$\bar{\sigma} = \sigma_0(T) + K_2 \exp(-K_3 T)\sqrt{1 - \exp(-K_4 \exp(K_5 T)\bar{\varepsilon}_p)}\,\dot{\bar{\varepsilon}}_p^{m_0 \exp(m_1 T)} \tag{2}$$

$$\begin{cases} \bar{\sigma} = \sigma_0(T) + (\alpha(T) f_H + (1-\alpha(T)) f_V)\dot{\bar{\varepsilon}}_p^{m_0 \exp(m_1 T)} \\ \alpha(T) = \alpha_1 - \alpha_2(T - T_0) \\ f_H = K_6 \bar{\varepsilon}_p^{\,n} \\ f_V = K_7(1 - \exp(-K_8 \bar{\varepsilon}_p)) \end{cases} \tag{3}$$

$\sigma_0(T)$ is the initial yield stress depending on temperature. It's expression is given by Eq. (4):

$$\sigma_0(T) = \sigma_0\left(1 - \frac{T}{T_m}\exp\left(Q\left(1 - \frac{T_m}{T}\right)\right)\right) \tag{4}$$

where σ_0=134.6MPa is the initial yield stress at ambient temperature, T_m=627°C is the melting temperature and Q=0.556.

According to uniaxial tensile test results, all the parameters have been identified using a gradient based optimization procedure to obtain the final set of optimized constants for the whole forming conditions, as shown in Table 1 to Table 3.

Table 1: *Parameters of Ludwick's model.*

K_0 (MPa)	537.4
K_1 (MPa/°C)	0.98
n_0	0.57
n_1 (1/°C)	$7.2\ 10^{-4}$
m_0	$8.8\ 10^{-5}$
m_1 (1/°C)	$3.2\ 10^{-2}$

Table 2: *Parameters of Voce's model.*

K_2 (MPa)	485.96
K_3 (1/°C)	$4.5\ 10^{-3}$
K_4	0.94
K_5 (1/°C)	$9\ 10^{-3}$
m_0	$9.2\ 10^{-5}$
m_1 (1/°C)	$3.2\ 10^{-2}$

Table 3: *Parameters of H-V model.*

α_1	0.68
α_2 (1/°C)	$2.5\ 10^{-3}$
K_6 (MPa)	633.11
n	0.61
K_7 (MPa)	136.82
K_8	28.14
m_0	$9.3\ 10^{-5}$
m_1 (1/°C)	$3.2\ 10^{-2}$

The comparison between experimental data and predicted flow stresses by the three models are shown in Figure 5 and Figure 6 for respectively $0.02s^{-1}$ and $2s^{-1}$, for the three temperatures.

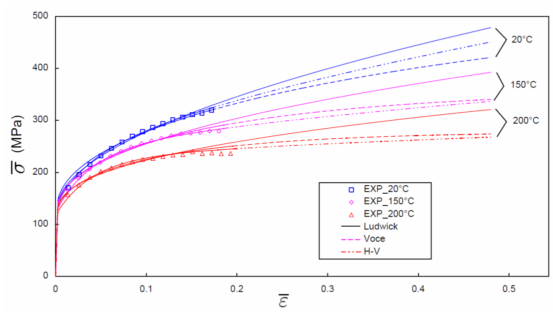

Fig. 5 *Predicted Flow stresses up to 50% of strain and comparison with experimental data for a strain rate of $0.02s^{-1}$.*

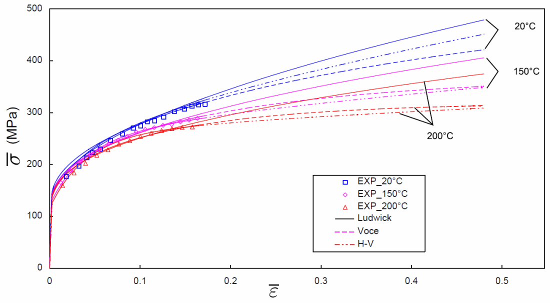

Fig. 6 *Predicted Flow stresses up to 50% of strain and comparison with experimental data for a strain rate of 2s-1.*

All the three identified hardening laws give a reasonable flow stress description for all the testing conditions within the measured strain ranges (below 18%). But they exhibit significant different extrapolations for high strain levels. For Ludwick's hardening model, the predicted flow stresses show a monotonic increasing character while the Voce's and H-V model both show a saturation stress state for high strains, especially at high temperature and low tensile speed.

Because the parameters are identified by the flow stresses from uniaxial tensile tests, a clear uncertainty exists when the hardening modelling is required for the prediction of forming limit curves at high strain levels. The hardening law influence on the prediction of FLCs is discussed in the last chapter of this work.

3.2 IMPERFECTION FACTOR

As already demonstrated in previous studies [8], the predictive forming limit curves from M-K model are very sensitive to the value of the imperfection factor f_0. A calibration step is then essential to fix the value of f_0. The values of three typical points (uniaxial tension (UT), plane strain tension (PT), biaxial tension (BT)) on the experimental FLCs can be used as input experimental data. Comparing the input experimental values to the simulated ones by means of a minimum cost function, the best fit value of f_0 can be determined.

The calibration method based on the PT point is preferred, it constitutes the best compromise for all the temperatures [8] and it permits predictions of accurate forming limits near the plane strain region, without any influence of the modelled yield criterion. This region is frequently the critical one for the forming of industrial parts. With the proposed calibration method, the calibrated f_0 values from the identified Ludwick's hardening model under each forming condition are shown in Table 4.

Table 4: *Calibrated f_0 for the different forming conditions.*

Temp (°C)	Strain rate (s^{-1})	f_0
20	2	0.9507
150	2	0.97
200	2	0.9927
150	0.2	0.99
200	0.2	0.99985
150	0.02	0.99985

One can see in Table 4 that the value of the calibrated f_0 varies with temperature and strain rate for this hardening law.

4 DISCUSSION

The aim of this chapter is to discuss the influence of hardening law and imperfection factor on the predictions of FLCs for all the forming conditions. Then the ability of the M-K model to predict forming limits is evaluated for these conditions.

4.1 CONSTANT IMPERFECTION FACTOR

Firstly, a constant value of the imperfection factor is chosen to predict the FLCs with the Ludwick's model. In literature, a classical value for the imperfection value is 0.996 ([11],[7]). For this value, the comparison between predictions and experimental FLCs are shown in Figure 7.

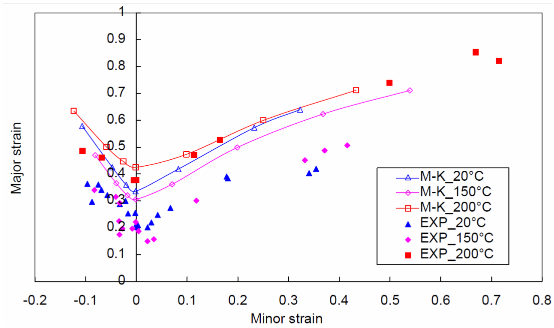

Fig. 7 *Predicted FLCs by Ludwick's model with constant f_0 = 0.996 at 2 s^{-1}.*

The predicted FLCs show a good tendency of the temperature sensitivity. But the predicted FLCs deviate from experimental results, especially at 20 and 150°C and an overestimation of all the predicted FLC_0 values is found. These results are in accordance with the ones from Table 4, the imperfection value must depend on temperature to predict reliable FLCs.

4.2 VARYING IMPERFECTION VALUE

By using Ludwick's law, the calibrated f_0 values from Table 4 are used to predict FLCs for the tested temperatures and strain rates, the results are presented in Figure 8 for 150°C.

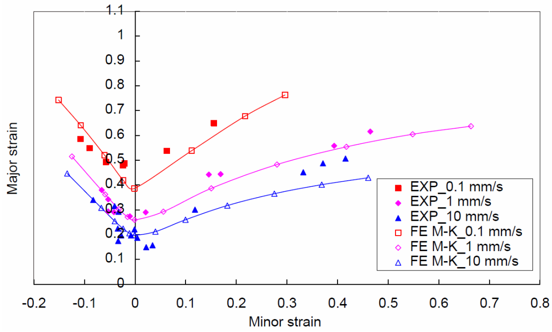

Fig. 8 *Predicted FLCs at 150 ℃ with Ludwick's model and varying imperfection factor.*

Figure 8 shows that good formability predictions are obtained at 150°C over the strain rate range, especially for the left hand side of the FLCs. Same conclusions can be drawn at 200°C. The little conservative prediction in the right hand side of the FLD is certainly caused by the isotropic yield criterion used in this study. A more realistic anisotropic yield criterion could improve predictions in this zone. Finally, the FE M-K model could be an efficient tool on condition that the geometrical imperfection was calibrated for each forming condition. Nevertheless, only one test in plane strain condition is sufficient to calibrate the model and to plot the whole FLC.

The same procedure is applied for the Voce's hardening law. Calibrated f_0 at a strain rate of $2s^{-1}$ are given in Table 5.

Table 5: *Calibrated f_0 for Voce's hardening law.*

Temp (°C)	Strain rate (s^{-1})	f_0
20	2	0.9908
150	2	0.997
200	2	0.99999

Predicted FLCs for the strain rate of $2s^{-1}$ are presented in Figure 9.

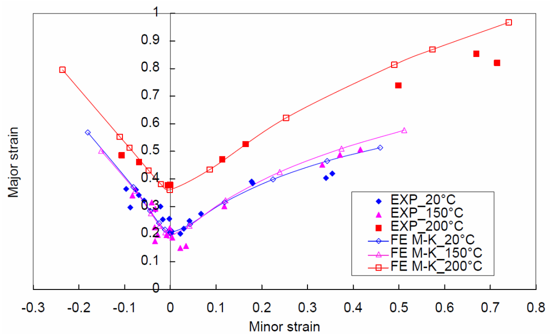

Fig. 9 *Predicted FLCs by Voce's hardening law with temperatures at a strain rate of $2s^{-1}$.*

For a strain rate of $2s^{-1}$, the Voce's hardening model gives a good FLCs prediction over the tested temperature range. Unfortunately, for lower forming speeds, the Voce's model cannot give reasonable FLCs predictions since the imperfection value at 200°C in Table 5 is already very close to 1 for a strain rate of $2s^{-1}$. This may be explained by an overestimation of the saturation phenomenon on the flow stress which can be a consequence of the imprecision in the extrapolation of the hardening law for large strains.

For the H-V model, calibrated f_0 at a strain rate of $2s^{-1}$ are given in Table 6.

Table 6: *Calibrated f_0 for H-V hardening law.*

Temp (°C)	Strain rate (s^{-1})	f_0
20	2	0.975
150	2	0.999
200	2	0.99995

Consequently, the predicted FLCs for a strain rate of $2s^{-1}$ and for the H-V model are presented in Figure 10.

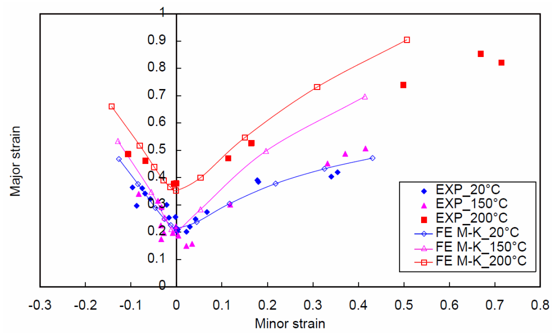

Fig. 10 *Predicted FLCs by H-V hardening law with temperatures at a strain rate of $2s^{-1}$.*

From Figure 10, a rather good correlation is observed at 20°C, while for higher temperatures, the predicted FLCs are overestimated in the right hand side of the FLD, especially for biaxial strain paths. Like Voce's hardening model, the mixed H-V model is not able to predict accurately forming limits at high temperatures and low forming speeds.

5 CONCLUSIONS

From this work, the following conclusions can be drawn:

- Temperature and strain rate play a predominant role on the formability of AA5086 sheet metal. The formability is improved with temperature and decreases with strain rate. The strain rate effect is emphasized for high temperatures.
- The calibrated values of the geometrical imperfection of the M-K model vary with the forming conditions which limits the use of the predictive M-K model without any experi-

mental data. Nevertheless, only one test in plane strain condition for each forming condition can be sufficient to calibrate precisely the model and to give an accurate estimation of the whole FLC.

- Definition of the imperfection value is very simplistic in the M-K model and does not take into account complex phenomena at the scale of the microstructure, like dislocation movements or recrystallization mechanisms which are affected by the forming temperature or strain rates. A more complex formulation of the imperfection factor should be necessary to improve the M-K model.
- The hardening model plays a great role in determining the FLCs from FE M-K model. The calibrated imperfection value is coupling with the choice of the hardening model. Ludwick's model permits to predict FLCs for all the forming conditions while Voce's and H-V models are not able to give accurate FLCs for high temperatures and low forming speeds.

6 ACKNOWLEDGEMENT

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